NASA GW-EM Task Force Report

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Acknowledgement of Consultants, Contributors, Community Input

We thank individuals who have provided significant input:

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Eric Howell (OzGrav, University of Western Australia)

Leo Singer (NASA/GSFC)

We thank leadership teams of the current and in-development missions.

We thank the GW-EM community for helpful input.

Executive Summary

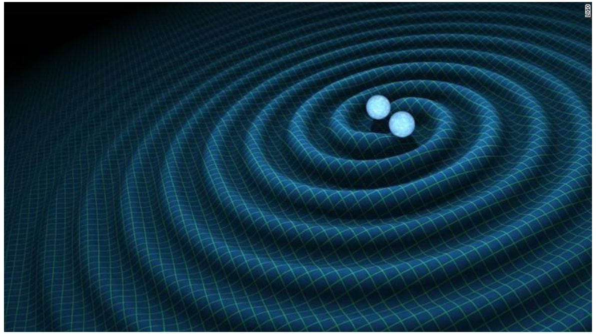
- NASA missions played a critical role in the discovery and characterization of the first binary neutron star merger (GW170817)

- In the near future, the balanced mission portfolio is well-positioned to continue to make major contributions to EM counterparts of gravitational-wave sources. Enhanced target-of-opportunity capabilities, improved communication and coordination, and improvements to Guest Investigator/Observer and Research and Analysis programs, could further augment the science return.

- By the mid-2020’s, NASA runs a serious risk of lacking critical observational capabilities for supporting gravitational-wave science goals. Current workhorse facilities (*Fermi, Swift, Chandra, HST*) are well past design lifetimes and lack suitable replacements. In addition, new capabilities (wide-field UV imaging, improved sensitivity at high energies) are needed to realize the full scientific potential of gravitational-wave detectors.

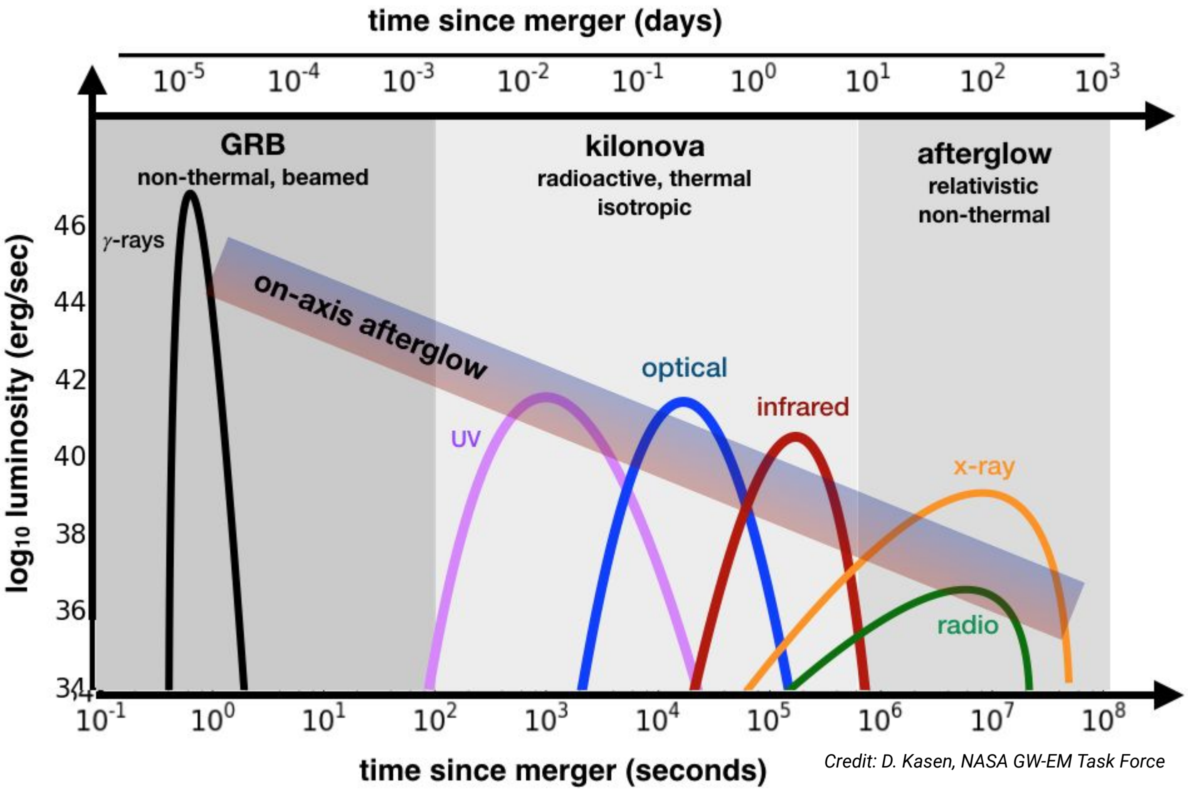
A New Era of Gravitational-Wave Astronomy

- Gravitational waves: ripples in curvature of spacetime caused by accelerating masses; prediction of General Relativity
- Multi-decade effort to build sufficiently sensitive ground-based interferometers (LIGO Livingston, LIGO Hanford, and Virgo) for *high-frequency* (~ 10-10^4 Hz) GWs
- Observing runs in “Advanced” configuration began in 2015
- Almost immediately made first direct detection of signal from binary black hole merger (GW150914)
- Nobel prize in Physics awarded in 2017 (Barish, Thorne, and Weiss)
- **Expectation: neutron star mergers (BNS or NSBH) should be accompanied by light**

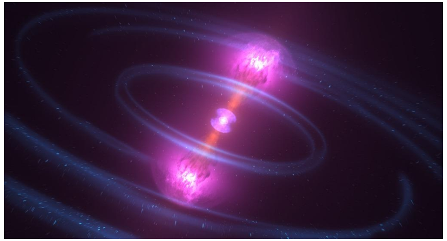


LIGO Hanford Interferometer

Electromagnetic (EM) Counterparts Overview



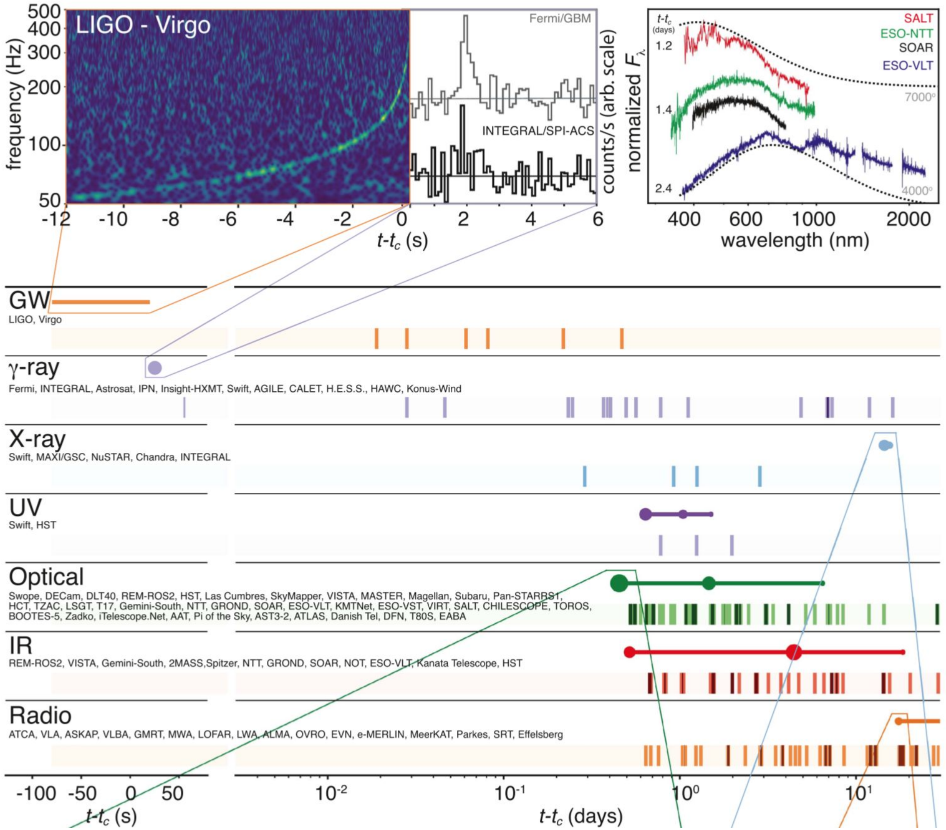
Credit: D. Kasen, NASA GW-EM Task Force



- Gamma-ray burst (GRB) and On-Axis Afterglow: Relativistic jet viewed within cone
- Kilonova: Radioactive glow from heavy elements, isotropic
- Off-Axis Afterglow: Relativistic jet viewed after lateral spreading
- **Panchromatic phenomenon with a variety of time scales**

Critical role of NASA missions in GW170817

- GW170817 EM Observations
  - GRB - Fermi, INTEGRAL*
  - UV kilonova - Swift, HST
  - IR kilonova - Spitzer, HST
  - Host Galaxy - HST
  - X-ray afterglow - Chandra, XMM*, NuSTAR, Swift
- Significant NASA observation time
  - HST - 65 orbits (10 programs)
  - Chandra - 975 ks (11 programs)
  - Swift - 721 tiles
- > 500 refereed papers on GW170817
- NSF Press Conference with NASA presence + huge media campaign



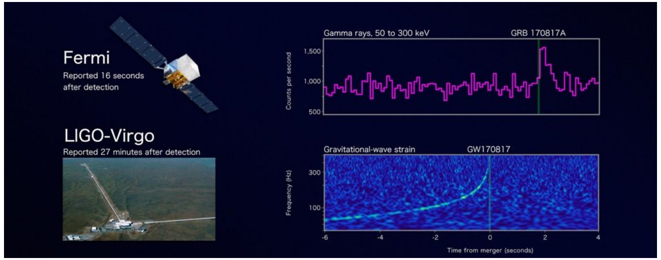
Abbott et al. 2017, ApJL, 848, L12

* ESA missions with NASA involvement

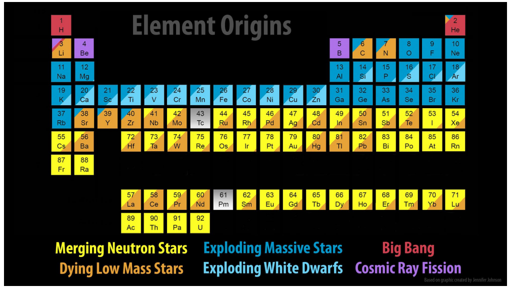
Science Enabled from GW170817 by NASA Missions

- Fundamental physics
  - Speed of gravity - Fermi
  - Hubble Constant - Chandra, HST
  - Neutron Star Equation of State - Fermi, Swift, HST
- Production of Heavy Elements
  - UV kilonova - Swift, HST
  - IR kilonova - HST, Spitzer
- Relativistic Jet Formation and Structure
  - Origin of short GRBs - Fermi
  - Off-axis structured jet afterglow - Chandra, HST, XMM
- Host Galaxy
  - Progenitor Age and Formation Channels - HST

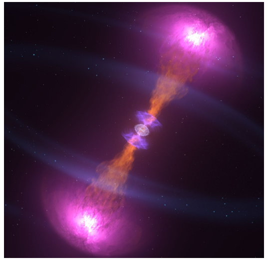
- Additional progress on all topics requires statistics from a population of GW-EM counterparts



Credit: *NASA SVS*



Credit: Jennifer Johnson/SDSS / CC BY 2.0 (modified)



Credit: NASA SVS

Task Force Charge (Terms of Reference)

1. For the currently operating NASA missions, assess:
    a. Their current contributions, or potential for contributions, to GW-EM Astrophysics
    b. Obstacles and barriers that need to be addressed for their optimal use including observations, data access, analysis, and interpretation of the data.
    c. Existing gaps in either/both facilities and operations
2. For present and future operations, identify
    a. A protocol to optimize the role of NASA in EM follow-ups of LIGO and LIGO A+ sources
    b. How this protocol might change over time as more GW events are found and extensive campaigns on individual mergers are replaced by studies of merger populations
3. Investigate top-level needed capabilities for the distant (>10 yrs) future, in light of anticipated GW-EM science drivers and already approved NASA missions. Identify specific actions to explore the feasibility of such capabilities (e.g., forming study teams).
4. Identify near- and long-term practices NASA should adopt to optimize GW-EM return from its missions (e.g., R&A, archives format, etc.).
5. Address ways to optimize interagency collaboration between NASA and NSF.

Task Force Formulation

- Initiated by Rita Sambruna and Valerie Connaughton with Paul Hertz's agreement
- Task Force Membership
    - Co-chairs representation from NASA centers with significant involvement in GW-EM science (GSFC, MSFC, JPL/Caltech)
    - 3 other members from US Universities
    - Leaders in subject areas relevant to GW-EM counterparts (GRBs, kilonovae, afterglows)
    - Experienced with the current fleet of NASA missions doing GW-EM science (Project, Instrument Teams, Users)
    - Important roles in next generation NASA multimessenger missions (leading or participating in mission concepts on scales from CubeSats to Probes/Flagships)
- Timeline
    - TOR signed - March 15, 2019
    - Membership formalized - April 1, 2019
    - Senior Review Report - June, 2019 - "The recently formed NASA Gravitational Wave–Electromagnetic Counterpart Task Force may provide a natural forum for developing these strategies and tools. It would be beneficial for this task force to host a focused meeting with leaders of the missions discussed in this report."
    - Final Presentation - December 17, 2019

Task Force Key Finding #1: The Past

The joint discovery of gravitational waves and electromagnetic radiation from the binary neutron star merger GW170817 was a watershed moment for astrophysics. NASA missions played a critical role in this discovery, from constraining the speed of gravity, to determining the site of heavy (r-process) element formation, to furthering our understanding of the formation and structure of relativistic jets.

Key open questions explored by joint GW-EM observations of compact binary mergers

- Can binary neutron star mergers reproduce the relative and total abundances of heavy (r-process) elements?
- What is the current expansion rate of the Universe (Hubble constant)?
- What conditions are necessary to produce relativistic jets, and what is their composition/structure?
- What is the equation of state of dense nuclear matter?
- Do black hole - neutron star and binary black hole mergers produce electromagnetic signals?

GW Network Landscape

Anticipated improvements:

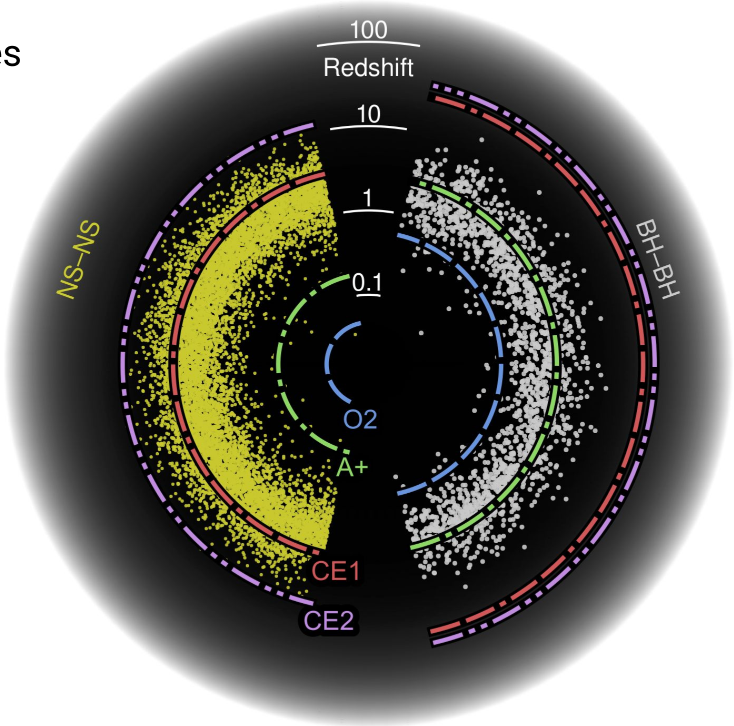
More GW detectors
Increased GW sensitivity

➡

Improved GW localizations
Increased GW detection rates
Increased distance horizon

Observing Run	Timescale	BNS Rate (yr^{-1})	BNS Range (Mpc)	Redshift
O1: LIGO	2015-2016	0.05-1	80	0.02
O2: LIGO/Virgo	2017-2018	0.2-4.5	100 / 30	0.02
O3: LIGO/Virgo	2019-2020	0-13	110-130 / 50 / 8-25	0.03
O4: LIGO/ Virgo/KAGRA	2021-2023	0.6-62	160-190 / 90-120	0.04
O5 (A+): LIGO/ Virgo/KAGRA/India	**late-2024+**	**10-200 / >30**	**330 / 150-260 / 130+**	**0.07**
Voyager	~2030?	>daily	1000	0.4
Cosmic Explorer 1	2035-2040	>hourly	>10,000	1.4
Cosmic Explorer 2	~2045	>hourly	All	10

Funded, Not yet Funded



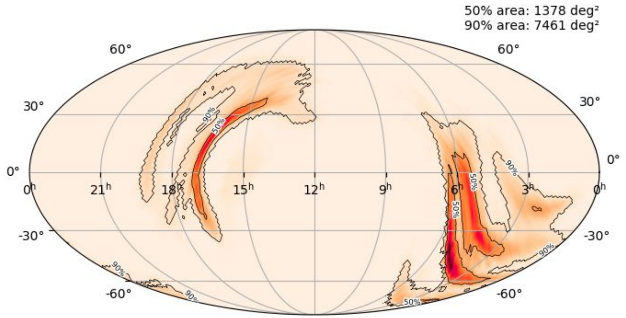
Reitze et al., arXiv: 1903.04615

Data:
LIGO, Virgo, and Kagra Collaborations et al. arXiv:1304.0670 (updated 9/2019)
Burns 2019, arXiv:1909.06085
Leo Singer, private communication, updated version of Observing Scenarios, LVC, in-prep

Recent Results from LIGO/Virgo O3 (April 1, 2019 - present)

- Public Alerts include: 41 non-retracted detection candidates (as of Dec 16, 2019)
  - BBH - 26 events >92% BBH probability
  - BNS - 5 events >49% BNS probability (1 event >90%)
  - NSBH - 5 events >68% NSBH probability
  - Mass Gap - 3 events >95% Mass Gap probability
  - Terrestrial? - 2 events
- Signals are high probability of being detections, but nature of components is less confident
- Maximum mass of neutron star/ minimum mass of black hole is unknown, mass uncertainties are large, so classifications are uncertain

- No credible electromagnetic counterparts detected despite follow-up efforts
- 1 additional Low-significance potential joint sub-threshold GW-GRB (GCN 25406)
- Potential for EM counterparts if NS is one of the components

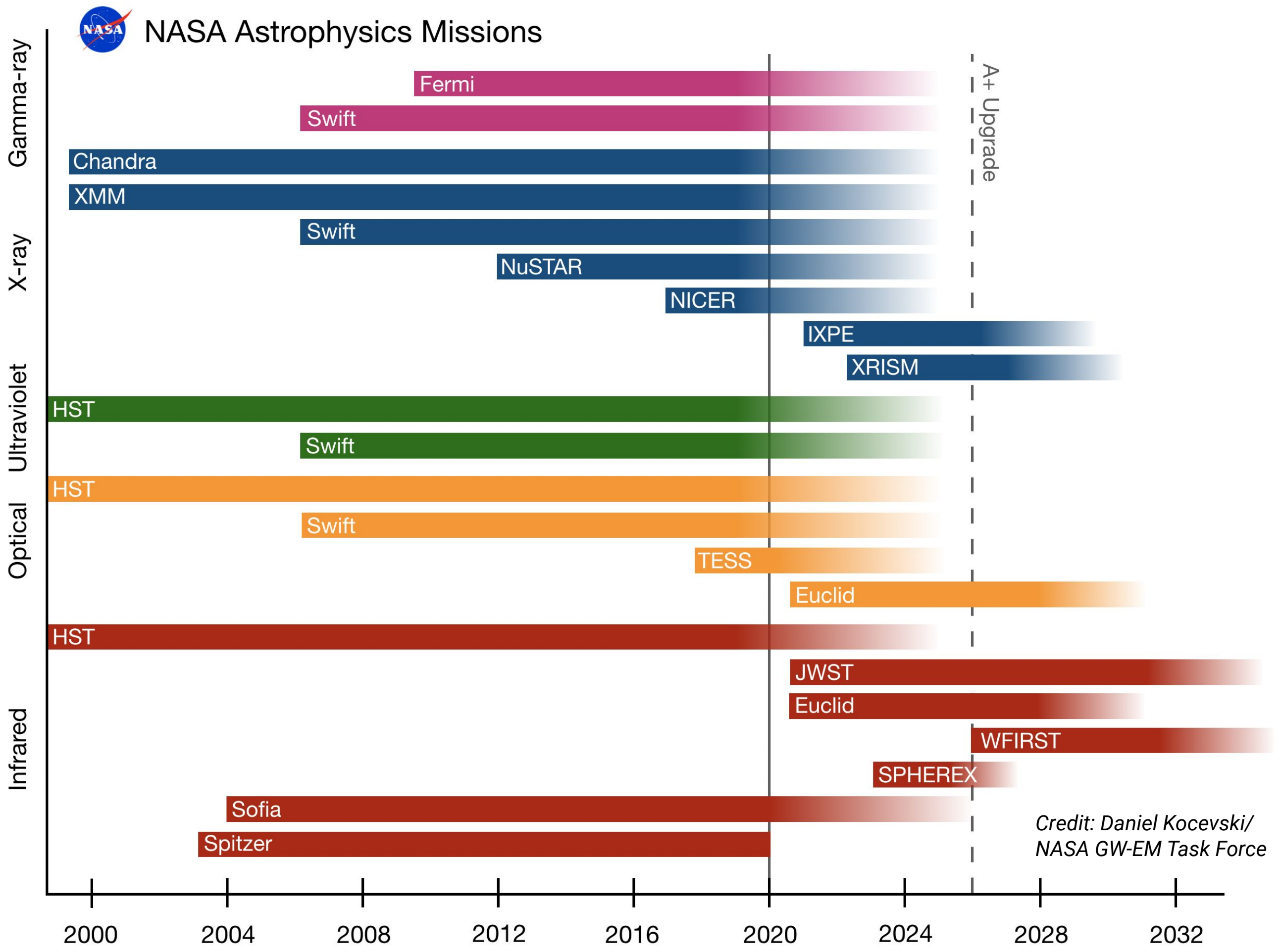


BNS S190425z
FAR = 1 per 69834 years
LIGO Livingston, Virgo only
https://gracedb.ligo.org/superevents/S190425z/view/

Data from: https://gracedb.ligo.org/superevents/public/O3/

Task Force Key Finding #2: The Present

In the present/near-future (O3+O4 Observing Runs, 2019-2023), NASA is well-positioned to capitalize on the exciting scientific opportunities in (high-frequency) gravitational wave astronomy. As highlighted in the 2019 Astrophysics Senior Review of Operating Missions, the portfolio provides a suite of capabilities that is "greater than the sum of its parts", and will contribute significantly to the major questions posed above. The science return in this area from currently operating and approved (i.e., in development) missions could be maximized by: a) enhanced target-of-opportunity capabilities; b) improved communication and coordination; and c) adjustments to GO/GI and R&A programs.



CubeSats/SmallSats/Balloons/ISS-Payloads may play a complementary role, but are not included specifically

- Many current missions are well past design lifetimes
- Downside of a balanced mission portfolio is little/no redundancy in critical capabilities
- No replacements planned for multiple "workhorse" GW-EM facilities
- Future mission portfolio leaves significant gaps in capabilities (e.g. gamma-ray, UV)
- Gaps could coincide with dramatic increase with GW detector sensitivity
- CubeSats/SmallSats/MOOs are complementary, but do not replace capabilities of large missions

Task Force Key Finding #3: The Future

For the A+ era and beyond (> 2025), NASA runs a serious risk of lacking critical observational capabilities for achieving the science goals described above. Not only are multiple gaps in the current suite of instrumentation not planned to be addressed, but presently available capabilities are not slated to be replaced when older missions are retired or become inoperable. Continued operations of the primary NASA GW-EM facilities (Fermi, Swift, Chandra, and HST) until suitable replacements are available would greatly benefit the science. Critical new capabilities in the NASA portfolio include wide-field / rapid-response UV imaging and wide-field high-energy (gamma-ray and/or X-ray) imaging. A commitment towards maintaining a balanced portfolio is critical to maximize scientific potential in the multi-messenger era.

Implementation

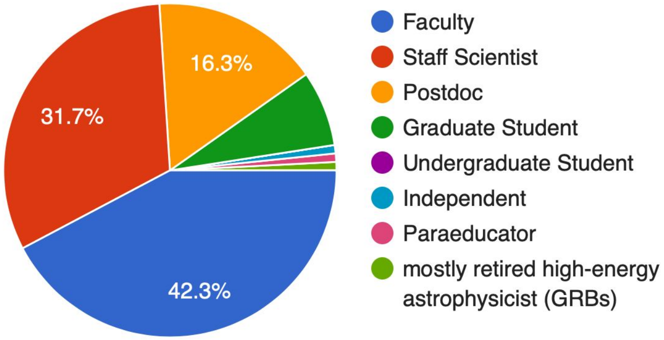
- NASA Mission Questionnaire & Follow-up Discussions
- GW-EM Community Survey
- Future Mission Capabilities: Source Rates and Detectability Analysis

Implementation: Mission Questionnaire

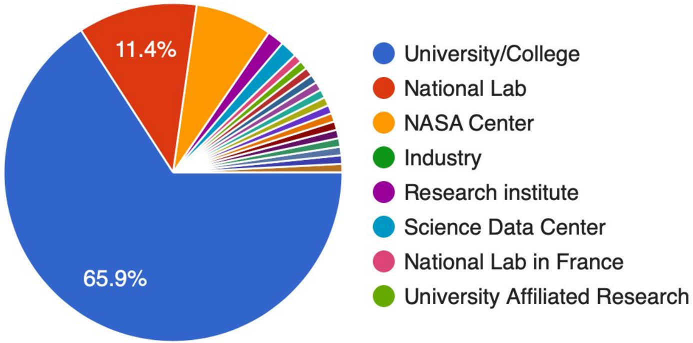
- Detailed Responses from Mission Leadership:
  - Current - Hubble, Chandra, Swift, Fermi, NuSTAR, NICER, TESS, XMM
  - In-development - JWST, WFIRST, IXPE
  - Used questionnaire to determine how NASA missions are approaching current and future multi-messenger science. Discussed preliminary findings with missions.
- Questions posed on topics including:
  - GW-EM Observation Strategy
  - Resources
  - Multiwavelength Coordination
  - Observing Plan Coordination
  - Data Analysis and Theory Proposals
  - Proprietary Periods
  - Archiving
  - Diversity

Implementation: GW-EM Community Survey

- Used open online survey to gauge the needs of the general GW-EM Community
- Solicited feedback from GW-EM community via:
    - LIGO/Virgo Open Electromagnetic Follow (LVEM) list
    - MMA SAG
    - GCN Circular (arranged especially with Scott Barthelmy)
    - Team email list (e.g. Fermi, Swift, GROWTH, etc.)
    - Sent to >2000 people, received 123 responses
- Topics:
    - Community Background and Use of NASA Facilities
    - Funding/R&A Programs
    - Joint Observing Programs
    - Proprietary Periods
    - Diversity
    - Archival Resources
    - Transient Communication Systems
    - Future Capabilities

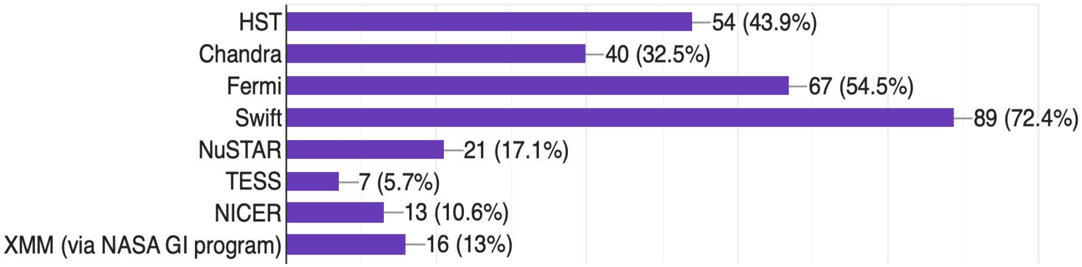


Classification: 63% observer, 19% theorist, 18% other
Wavelength bands studied: 52% Optical/UV/IR, 41% X-ray/gamma ray, 8% radio

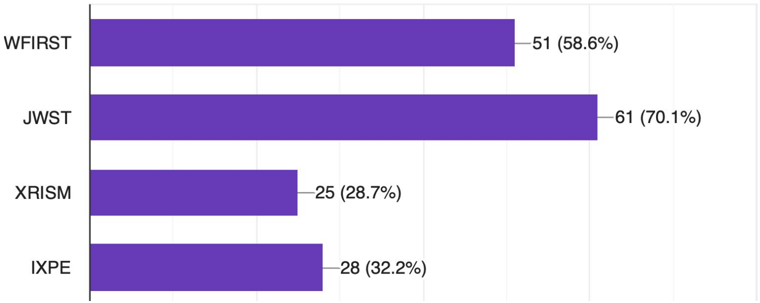


Implementation: GW-EM Community Survey

Community Survey: *Which NASA mission(s) do you apply for time on or use data from regarding GW-EM science?*



Community Survey: *Would you apply for time on upcoming missions for GW-EM science?*



- **Swift, Fermi, HST, Chandra** are most utilized missions for GW-EM science.
- **NuSTAR, NICER, TESS** can play important supporting role for rare bright events.
- **JWST, WFIRST** have significant community interest in GW-EM science in the next decade.
- **NASA high-performance computing** resources used by ~5% of respondents (and ~5% used NSF computing).

Implementation: Source Rates and Detectability Analysis to Guide Future Mission Capabilities

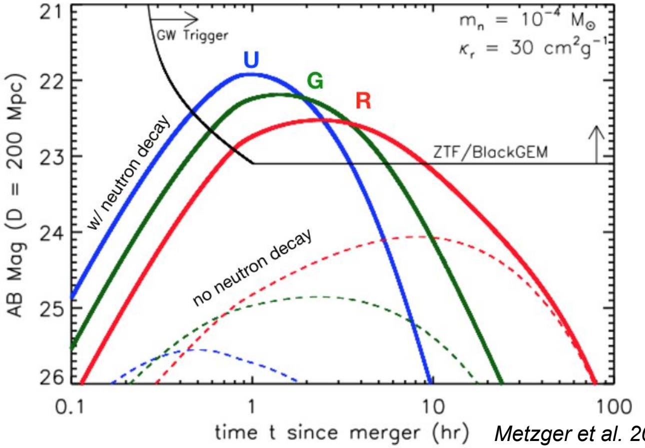
- Task force members analyzed potential source rates and detectability to help guide for future mission needs
- Using common assumptions, explored phase-space of 3 types of GW-EM counterparts rates in next decade:
    - Gamma-ray bursts
    - Kilonovae
    - Afterglows
- Observing capabilities needed for GW-EM science in next decade
- Technologies needed for GW-EM science in next decade

Top-Level Findings for Current and Planned Missions

- **2a) Enhance Target of Opportunity (ToO) capabilities** of current and planned missions
- **2b) Improve communication and coordination** within NASA missions, between NASA missions and observers, within the community, and with the NSF
- **2c) Adjustments to GI/GO and R&A programs**

2a. Enhance ToO capabilities: Lessons Learned

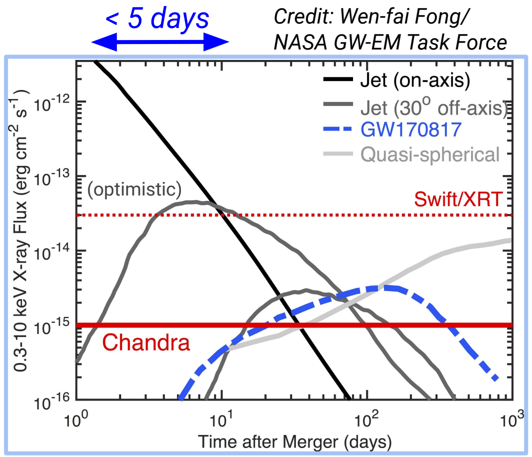
Ultraviolet/Optical: *What is the nature of the early kilonova emission (r-process radioactivity, free neutron decay or shock-cooling)?*



Metzger et al. 2015

X-rays: *What is the nature and occurrence rate of relativistic outflows from NS mergers?*

Credit: Wen-fai Fong/ NASA GW-EM Task Force



NS merger at 100 Mpc

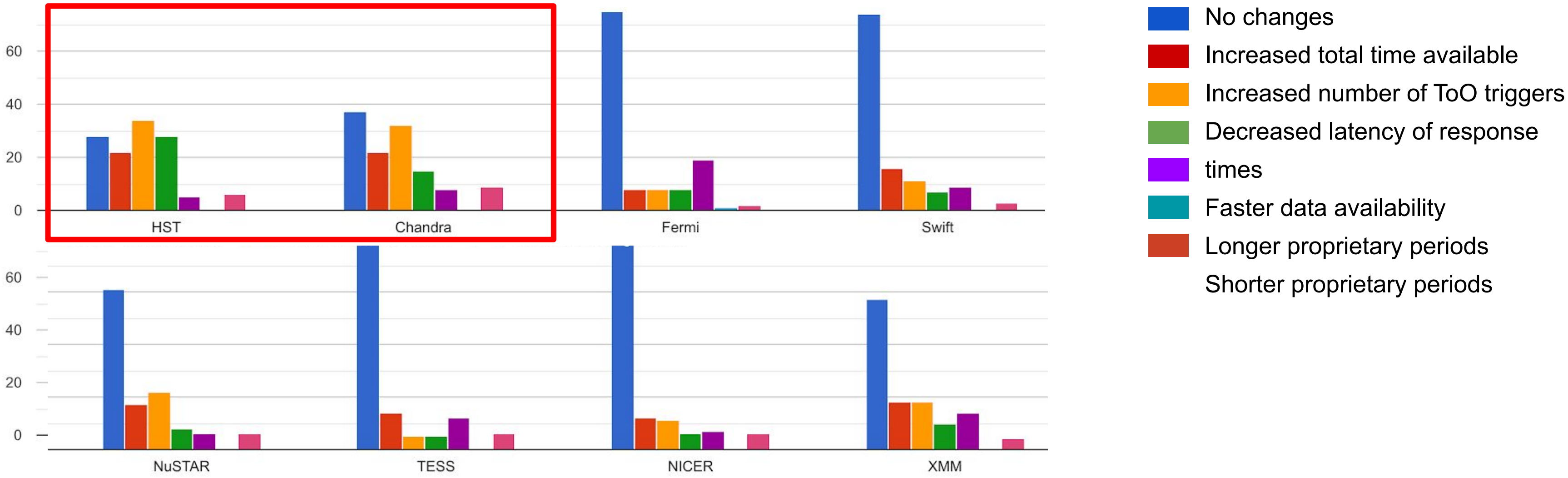
- ***HST*** **(UV),** ***Chandra*** **(X-rays), and Swift (UV/X-ray) are the only current NASA facilities** with the required sensitivities and angular resolution for regular detections of contemporary and near-future GW kilonovae and afterglows. In the UV band, *HST* and *Swift* are the only current **or** planned facilities.
- **Rapid observations in the first hours and days after merger** are crucial in distinguishing between models and therefore answering these fundamental questions for a population of NS mergers.
- Models of NS mergers and observations of GW170817 **thus motivate rapid ToOs as a high priority in these missions.**

2a. Enhance ToO capabilities of current missions

Identified need for changes primarily in Chandra and HST

Regarding potential changes to current missions, the community views the top priorities as (a) more ToO triggers, (b) increased observing time available for ToOs, and (c) reduced response time.

Community Survey: *What potential change to observing procedures/policies would you see as most beneficial to GW-EM science for current operating missions:*

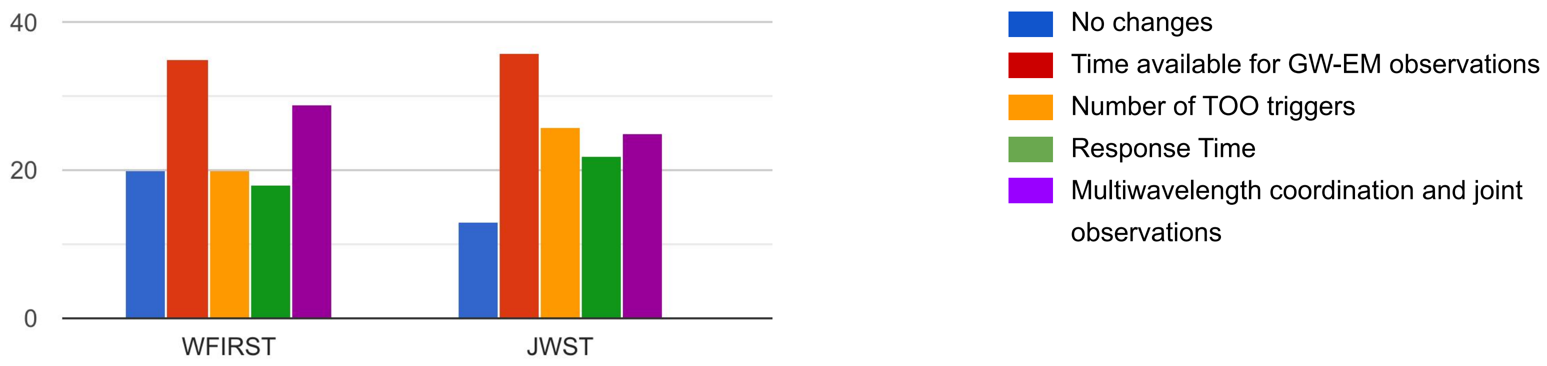


2a. Enhance ToO capabilities of planned missions

Identified need for changes primarily in JWST and WFIRST

For **planned missions**, the community's top priorities are planned (a) observing time available for GW-EM observations, (b) number of ToO triggers, and (c) response time.

Community Survey: *What potential change to observing procedures/policies would you see as most beneficial to GW-EM science for upcoming missions:*



2a. Enhance ToO capabilities of current and planned missions

Mission	Current or planned ToO capability?	Fastest Response	Number of fastest response ToOs in latest cycle	Limitations to increasing number of fast-response ToOs
HST	Y	<36 hr	1-2	Technical feasibility, 24/7 on-call staff for responding to ToOs
Chandra	Y	<5 days	8 GO + 4 DDT	Technical limitations leading to difficult scheduling
Swift	Y	<1 hr	Not Limited	Ground station contacts
NuSTAR	Y	<48 hr	500 ksec	Operations funding (lack of 24/7 on-call staff)
NICER	Y	<1 hr	Not Limited	Tools such as web visibility calculator
JWST	Y	<48 hr	8	Scheduling, technical
WFIRST	N	< 2 weeks	N/A	Funding

*Given growing community need, increased number of events, and technical limitations to decrease fastest response times, (a) **increasing number of fast ToOs** and (b) **ensuring ToO capability in planned** missions should be top priorities.*

2a. Enhance ToO capabilities of current and planned missions

Mission-specific findings:

- In time for O4 (2022), decreasing the latency for ultra-rapid ToOs on HST to <24-36 hours (currently 48 hours) would enable observations addressing key open questions surrounding the (kilonova) ejecta composition and power source.
- In time for O5 (2025), increasing the number of ultra-rapid (currently 1-2 per cycle) and disruptive (currently ~8 per cycle) ToOs on HST would enable observations that probe the diversity of ejecta properties in kilonovae. For comparison, we estimate ~ 18 kilonova detections per year on this time scale.
- In time for O5 (2025), increasing the number of very-fast ToOs (currently 8 available per cycle) on Chandra would enable observations probing the jet viewing angle and structure for a much broader sample of mergers. For comparison, we estimate ~ 5 off-axis afterglow detections per year on this time scale.
- For both HST and Chandra, a community follow-up program, with a pre-defined observing sequence, a well-defined trigger criteria focused on the most rare and critical events (bright, nearby, …), and zero proprietary period, triggered by the mission, may help reduce latency and achieve the prompt response science goals described above.
- For WFIRST, a robust ToO program with a response time requirement of < 48 hours and a data latency requirement < 12 hours would enable kilonova discovery for the reddest events. Such a capability may be uniquely sensitive to counterparts from black hole - neutron star mergers.

2b. Improved communication and coordination

Cross-Mission findings: MMA science would greatly benefit if:

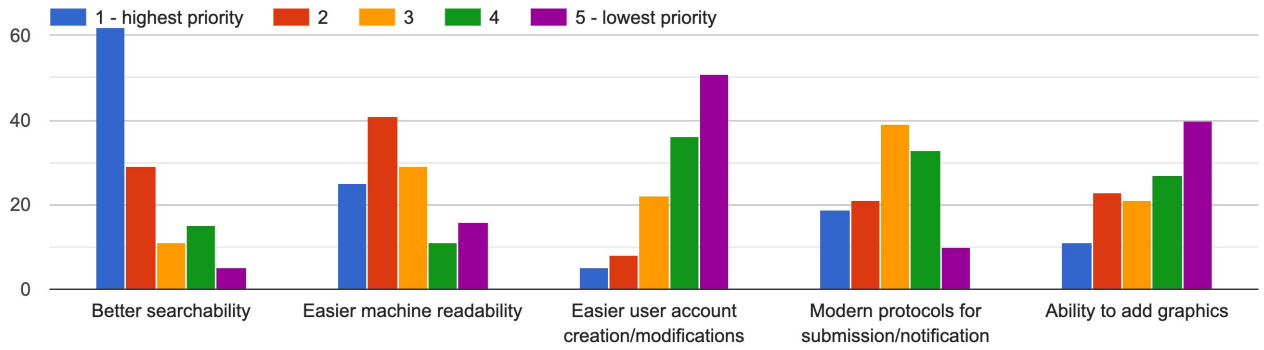
- Relevant NASA missions improved follow-up coordination amongst themselves to optimize the scientific return from the entire Astrophysics portfolio
  - Swift and HST established a protocol for rapid communication regarding UV observations of GW counterparts
  - Swift, NuSTAR, NICER, Chandra, XMM, IXPE, and XRISM established a protocol for rapid communication and (where possible) coordination regarding X-ray counterpart searches and follow-up
  - Gamma-ray monitors working together for detections, sub-threshold searches, and localizations enabled rapid identification of NS mergers and trigger follow-up observations

2b. Improved communication and coordination

Mission-independent findings:

- Communication between missions and the broader astronomical community would be improved if all NASA missions implemented common standards for reporting on planned and executed observations, and the detection of transient sources. These standards should be identical to those adopted by NSF-funded (e.g., LSST) and internationally funded (e.g., SKA) facilities.

Community Survey: *What improvements would you like to see [regarding transient communications systems], ranked?*



2b. Improved communication and coordination

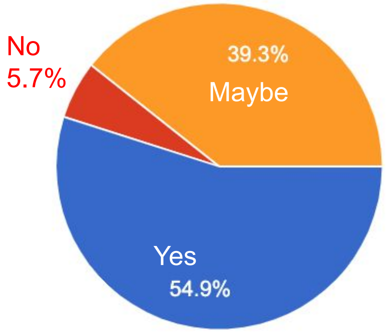
Mission-independent findings:

- As gravitational wave detectors improve in sensitivity and event rates correspondingly increase, archival searches will become an increasingly important tool in multi-messenger astronomy. The utility of NASA archives would be increased if: :
    - All NASA missions ensured that both data and data products are stored in common archives, with modern Application Programming Interfaces (APIs) and (where possible) abiding by common standards.
    - Improved advertisement of existing capabilities and development of new resources for cross-mission archival searches (both within NASA and between NASA missions and ground-based facilities) became a high priority for the community.
    - A funding mechanism to support community efforts to improve upon existing tools (e.g., GCN, TACH) and develop new resources/tools (e.g., Treasure Map, NED Gravitational-Wave Follow-Up service) to better coordinate community follow-up and sub-threshold coincidence searches (e.g. Fermi-GBM, Swift-BAT) would result in exciting new scientific opportunities.
    - Where possible, prioritizing the processing and dissemination of GW-EM observations would enable more efficient and effective follow-up by the community.

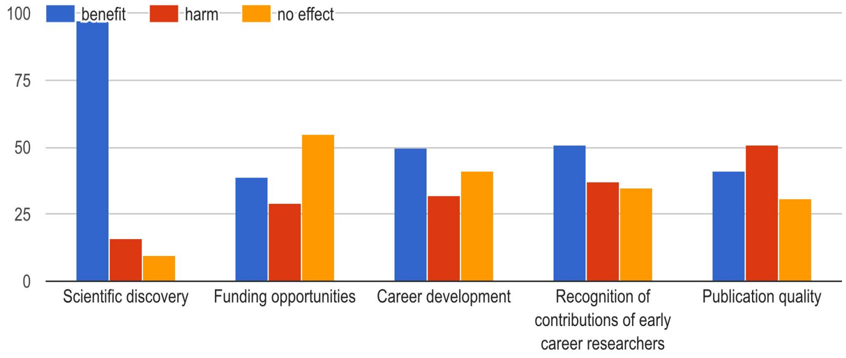
2c. Adjustments to GI/GO and R&A programs

- Community survey respondents **were positive about allowing multiple co-PIs**, which could help early career scientists get recognition as PIs and facilitate collaboration among groups.
- Most community survey respondents **favored shorter (< 1 month) proprietary periods**, believing this would enhance science discovery and benefit early career scientists

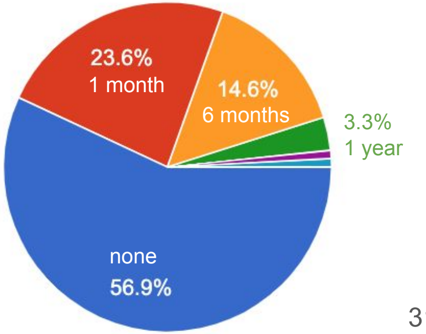
Community Survey: *Will allowing multiple co-PI's benefit early career researchers?*



Community Survey: *How would zero proprietary periods affect the following?*

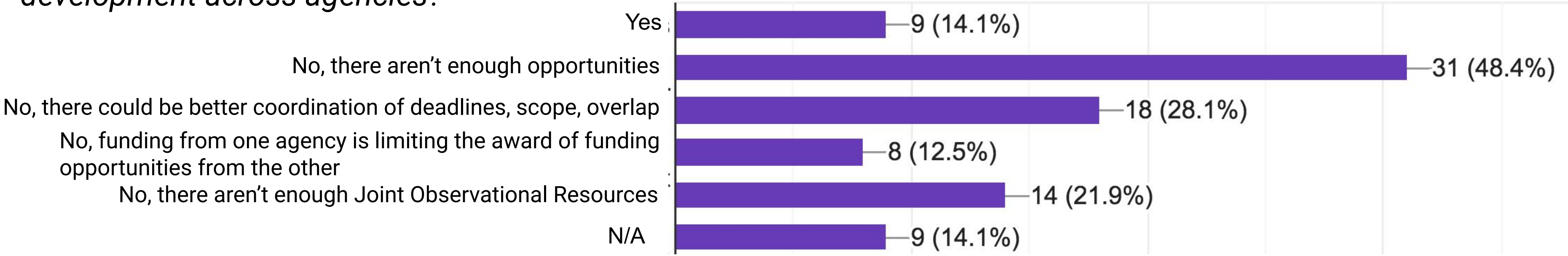


Community Survey: *What proprietary period for NASA missions would be most appropriate for GW-EM observations?*



2c. Adjustments to GI/GO and R&A programs

Community Survey: *Do you find funding opportunities appropriate for GW-EM science and/or technology development across agencies?*



- **48%** of respondents say there are **not enough funding opportunities** for GW-EM science and/or technology development.
- **28%** of respondents say there could be better coordination of deadlines and scope.
- When asked to identify the main barriers in current R&A programs to achieve GW-EM science, common themes include:
  - Lack of joint funding opportunities between NASA and the NSF
  - No NASA equivalent of "NSF Windows on the Universe: The Era of Multimessenger Astrophysics" Program
  - Lack of funding for theoretical studies and/or data analysis

2c. Adjustments to GI/GO and R&A programs

Joint observing opportunities (using most recent calls for proposals as of November 2019):

	Primary Program							
Joint Facility	***HST***	***Chandra***	***XMM***	***Swift***	***NuSTAR***	***Fermi***	***TESS***	***NICER***
HST		✓	✓					
Chandra	✓		✓					
XMM	✓	✓			✓			
Swift		✓	✓		✓		✓	
NuSTAR		✓	✓	✓				✓
Fermi								
TESS	✓							
NICER					✓			
NOAO	✓	✓				✓		
NRAO	✓	✓	✓	✓		✓		
INTEGRAL			✓			✓		
VLT			✓					
VERITAS						✓		
MAGIC			✓					
H.E.S.S.			✓					

2c. Adjustments to GI/GO and R&A programs

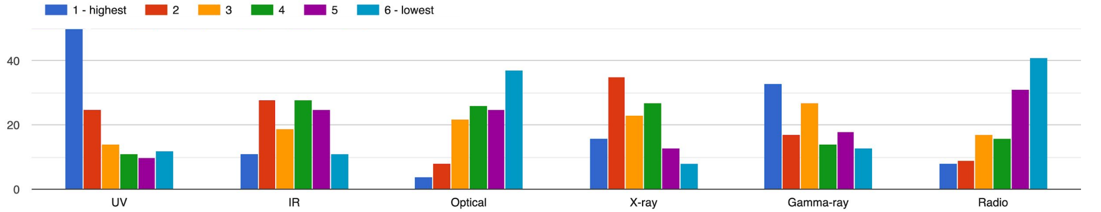
GI/GO and R&A Program Findings

- Following the successful model from HST, allowing co-PI's on GO/GI and R&A proposals would promote cooperation between groups and benefit early career scientists.
- For GW-EM science, the community strongly favors shorter (≤ 1 month) proprietary periods, as this was believed to significantly benefit scientific discovery potential, as well as career development and recognition of the contributions of early career researchers. At a minimum, missions should allow proposers to decrease the default proprietary time.
- Given the inherently multi-wavelength nature of this area of science, joint observing proposals played an important role in GW170817, and will continue to do so going forward. To improve opportunities for such joint programs in the future, we find:
    - NASA should maintain an updated list of joint observing opportunities and make this list available to the community.
    - NASA missions should pursue additional joint programs where scientifically relevant.
    - In addition to single agency calls, a joint funding program with the NSF (LIGO, LSST, etc.) would open new opportunities for novel multi-messenger programs.
- Given the rapid pace at which discoveries alter the field, the current ATP policy of soliciting grant proposals every two years may have a particularly negative impact on both theorists working in this science area, as well as observers reliant upon theory to guide counterpart searches.

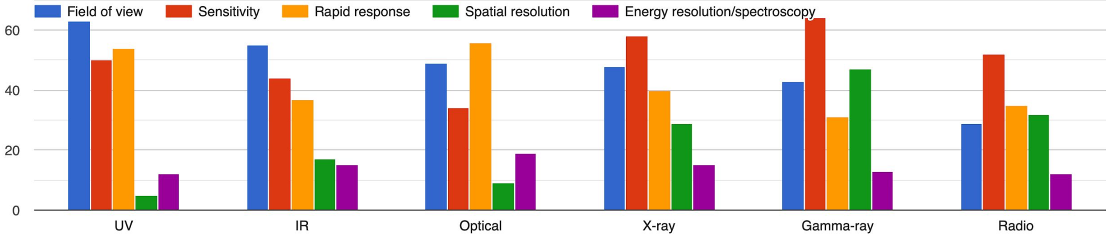
3a: Future Capabilities

- GW-EM Task Force guidance on needed capabilities is based on data from community and literature. We are not advocating for specific mission concepts.
- GW-EM science requires broad wavelength coverage, and NASA missions to maintain capabilities not possible from the ground, especially UV, gamma-ray, X-ray, and IR.
- Wide fields of view, fast response time, and sensitivity are critical to the detection, localization, characterization of GW-EM counterparts.
- The community showed a strong preference for mission(s) providing multiple needed capabilities, rather than a highly capable mission addressing a single (most pressing) need (e.g., Flagship).

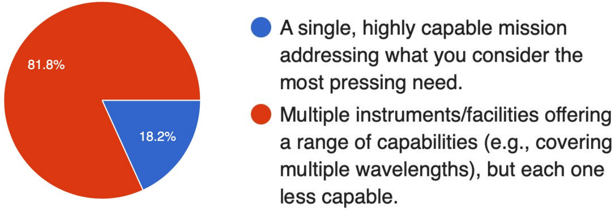
Community Survey: *Which bandpasses may be most lacking for GW-EM capabilities in the 2020's, especially after the next GW network upgrade (rank)*



Community Survey: *What is the most needed capability for GW-EM science in each bandpasses in the 2020's?*



Community Survey: *Given your priorities for the future above, which would you prefer?*



3a: Findings on Future Capabilities

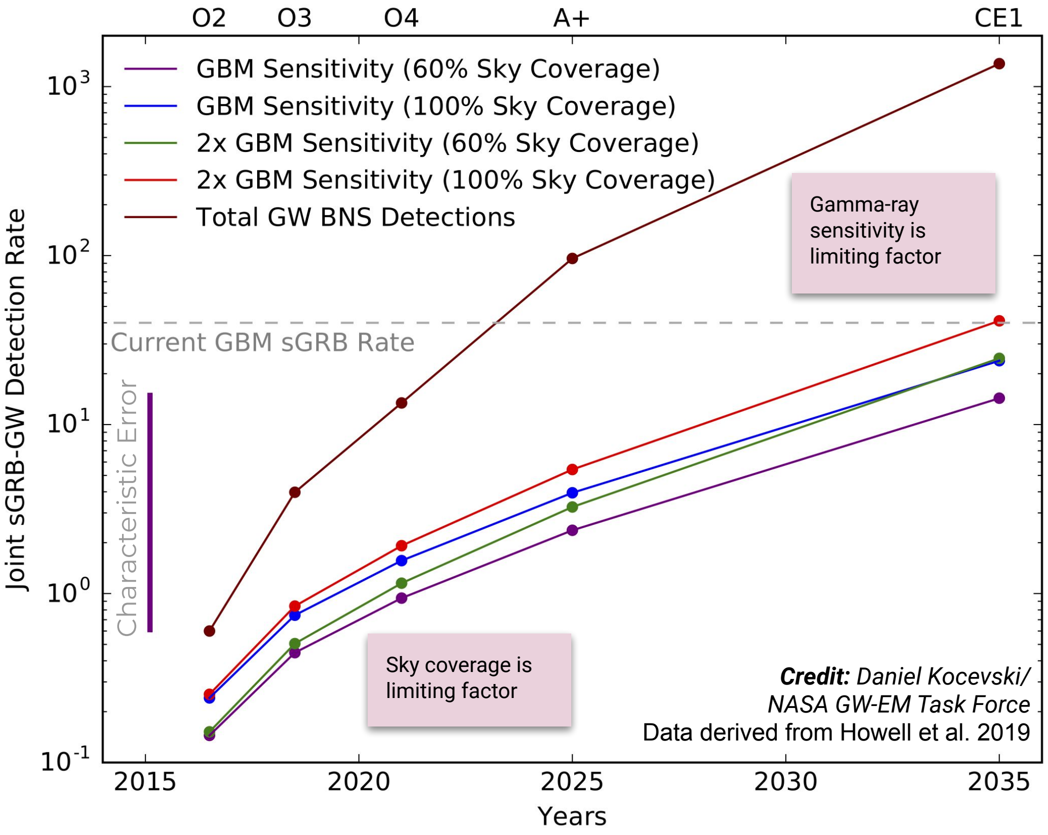
- Maintaining a balanced portfolio (in terms of wavelength, field-of-view, response time, sensitivity, etc.) is critical to achieve the full scientific potential of the multi-messenger era. To this end:
    - Maintaining operations for existing facilities, particular those most actively engaged in GW-EM science (*Fermi*, *Swift*, *Chandra*, *HST*), is critical towards achieving this portfolio balance, as no suitable replacements are currently planned.
    - The most critical **new** capabilities identified by the community for gravitational-wave science are wide-field UV imaging and improved sensitivity at high energies (gamma-ray, X-ray).
    - Where possible, ToO capability in future missions (including Flagships) would maximize contributions to GW-EM science.

3b: Findings on Key Enabling Technologies

- Rapid, high-bandwidth, up- **and** down-going communication would enable the earliest observations and most efficient detection of GW-EM counterparts
- High throughput UV detectors would enable identification of the emission mechanisms of early blue kilonova
- Improved sensitivity at gamma-ray (in particular keV-MeV) energies would increase the fraction of GW detections with EM counterparts
- Improvements to wide-field X-ray sensitivity would enable the rapid identification, precise localizations, and characterization of early X-ray counterparts

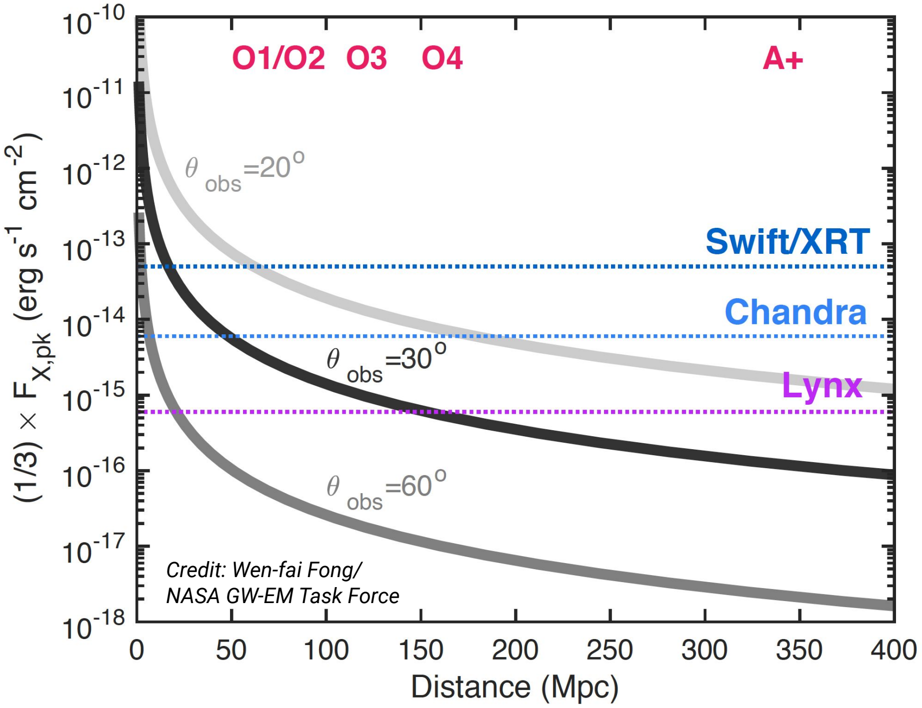
GW Counterparts: Gamma-ray Bursts

- Total BNS detections in GWs will grow by two orders of magnitude in the next decade
- Almost every detected sGRB will be accompanied by a GW detection by 2035-2050
- Increasing gamma-ray sky coverage is as important as increasing gamma-ray sensitivity to maximize future joint GW-sGRB detections
- Sub-threshold searches will be even more sensitive, but require continuous untriggered data be sent to the ground



Credit: *Daniel Kocevski/ NASA GW-EM Task Force*
Data derived from Howell et al. 2019

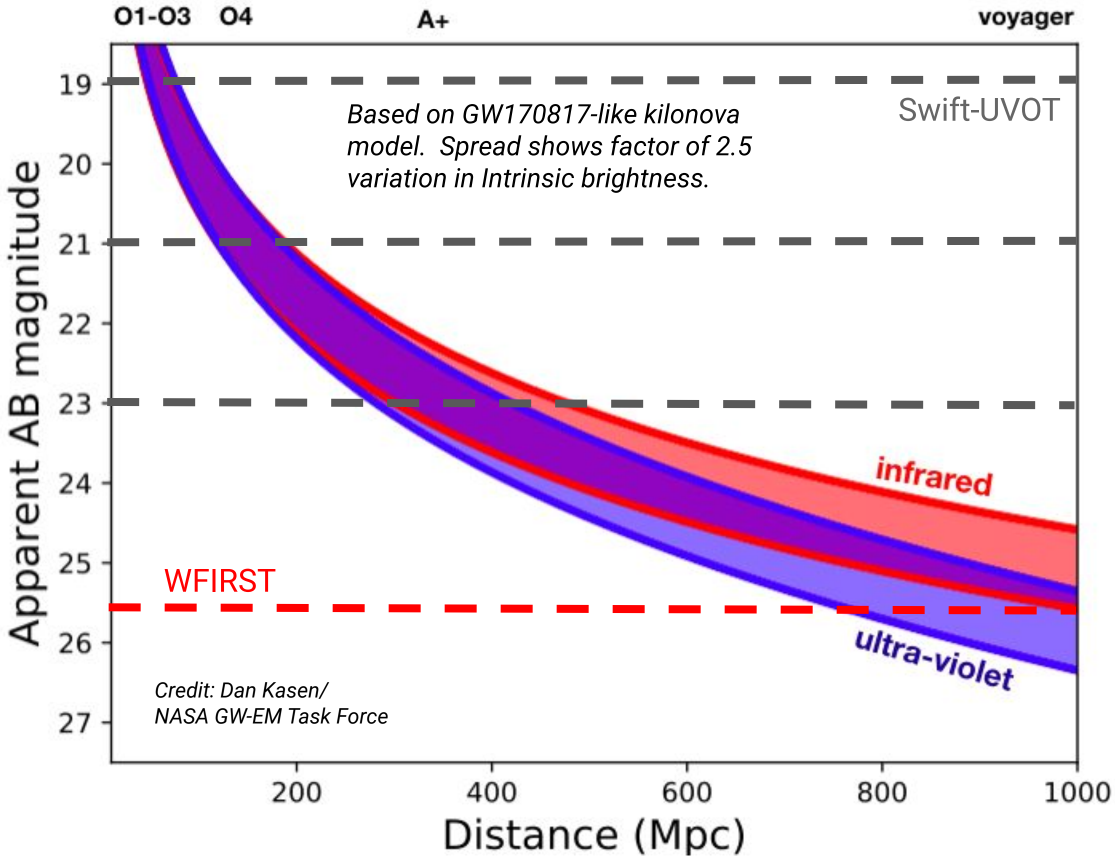
GW Counterparts: X-ray Afterglows



A conservative estimate of 3x below the peak flux has been used in these limiting calculations.

- For observer angles ≤30 degrees (40% of GW events and similar to GW170817), current NASA facilities are capable of detecting and characterizing X-ray afterglows through O4.
- Beyond O4, no current or planned X-ray mission has the sensitivity required to detect and characterize the X-ray counterparts to most NS mergers at observer angles >30 degrees.

GW Counterparts: Kilonovae



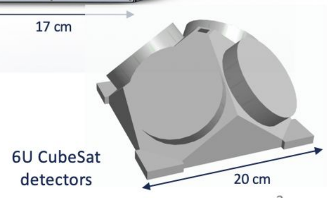
- UV peaks ~hours, optical peaks ~1 day, IR peaks ~few days
- Wide-field or tiling instruments ideal for discovery / Narrow-field, sensitive instruments best for characterization
- Swift/UVOT can tile ~1000 galaxies (~100 deg^2) to 19th magnitude in ~1 day
- O4 requires ~21 mag over ~100 deg^2 within a few hours
- A+ requires ~23 mag over ~50 deg^2 within a few hours
- WFIRST (0.3 deg^2 field of view) could follow-up identified counterparts, and could tile very well-localized GW detections

3c: Role of SmallSats in the GW-EM Science

- Small/Cubesats can play an important role in GW-EM science, particularly in areas where field-of-view / sky coverage is more critical than sensitivity.
- A primary drawback is the typically short lifetimes of individual SmallSats/ CubeSats.
- Could be mitigated by proposal opportunities allowing SmallSat/CubeSat networks with regular, planned replacement (e.g., GOES network).

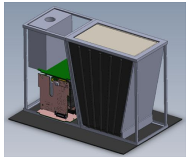
Glowbug

PI: Eric Grove (NRL)



BurstCube

PI: Jeremy Perkins (GSFC)



BlackCat

PI: Abe Falcone (Penn State)

Conclusions

- NASA missions will play a vital role in GW-EM science in the next decade
- Because of the multi-wavelength nature of GW-EM science, better cooperation between ground- and space-based facilities, improved communication and archives, and sufficient funding opportunities would improve the scientific return
- Investments in the next few years in missions designed for GW-EM science will make NASA at the forefront of discovery
- Additional mission-specific findings in auxiliary slides
- As the field evolves with additional GW-EM detections over the coming years, these findings should be revisited by convening another GW-EM Task Force

Mission Specific Findings

Hubble - Mission Specific Findings

- In time for O4 (2022), decreasing the latency for ultra-rapid ToOs on *HST* to <24-36 hours (currently 48 hours) would enable observations addressing key open questions surrounding the (kilonova) ejecta composition and power source. Automation of some of the steps in the ToO process (e.g., schedule building and verification, TDRSS uplink) may help facilitate a faster turn-around while decreasing the burden on operations staff (Slide 27).
- In time for O5 (2025), increasing the number of ultra-rapid (currently 1-2 per cycle) and disruptive (currently ~8 per cycle) ToOs on *HST* would enable observations that probe the diversity of ejecta properties in kilonovae. For comparison, we estimate ~ 18 kilonova detections per year on this timescale (Slide 27).
- For both *HST* and *Chandra,* a community follow-up program, with a pre-defined observing sequence, a well-defined trigger criteria focused on the most rare and critical events (bright, nearby, …), and zero proprietary period, triggered by the mission, may help reduce latency and achieve the prompt response science goals described above (Slide 27).
- An established protocol for rapid communication between *Swift* and *HST* regarding UV observations of gravitational-wave counterparts (Slide 28) would increase the returns for UV GW-EM science goals.
- For GI/GO ToO programs with potential scientific overlap, the development of a clear "decision tree", communicated to the PIs in advance, together with regular communication, will help to optimize the GW-EM science return and reduce redundancy.
- See also Slides 29, 30, and 34 for Mission-independent findings

Chandra - Mission Specific Findings

- In time for O5 (2025), increasing the number of very-fast ToOs (currently 8 available per cycle) on *Chandra* would enable observations probing the jet viewing angle and structure for a much broader sample of mergers. For comparison, we estimate ~10 off-axis afterglow detections per year on this time scale (Slide 27).
- For both *HST* and *Chandra,* a community follow-up program, with a pre-defined observing sequence, a well-defined trigger criteria focused on the most rare and critical events (bright, nearby, …), and zero proprietary period, triggered by the mission, may help reduce latency and achieve the prompt response science goals described above (Slide 27).
- A protocol for rapid communication and (where possible) coordination regarding X-ray counterpart searches and follow-up among *Swift*, *NuSTAR*, *NICER, Chandra, XMM, IXPE*, and *XRISM* (Slide 28) would be beneficial and may reduce redundancy.
- For GI/GO ToO programs with potential scientific overlap, the development of a clear “decision tree”, communicated to the PIs in advance, together with regular communication, wouls help to optimize the GW-EM science return and reduce redundancy.
- See also Slides 29, 30, and 34 for Mission-independent findings

Swift - Mission Specific Findings

- An established protocol for rapid communication regarding UV observations of gravitational-wave counterparts between *Swift* and *HST* would benefit GW-EM science (Slide 28).
- A protocol for rapid communication and (where possible) coordination regarding X-ray counterpart searches and follow-up among *Swift*, *NuSTAR*, *NICER, Chandra, XMM, IXPE*, and *XRISM* (Slide 28) would be beneficial and may reduce redundancy.
- Improved coordination and sharing of data analysis techniques for sub-threshold searches with other high-energy missions (e.g., *Fermi*-GBM) would significantly increase the likelihood of joint GW-EM detections.
- Providing BAT upper limit maps and a table summarizing observation history of GW triggers would enable archival investigations of independent candidate counterparts.
- See also Slides 29, 30, and 34 for Mission-independent findings

Fermi - Mission Specific Findings

- The public release of software packages used by the instrument teams (e.g., GBM localization algorithms and targeted search) would allow their performance to be independently verified and/or augmented by community members, thereby increasing the scientific return from the mission.
- Automated joint localizations between GBM/LAT and GW detectors would (in some cases) greatly increase the efficiency of counterpart recovery at e.g., X-ray and optical wavelengths.
- Providing GBM/LAT upper limit maps and a table summarizing observation history of GW triggers would enable archival investigations of independent candidate counterparts.
- See also Slides 29, 30, and 34 for Mission-independent findings

NuSTAR - Mission Specific Recommendations

- A protocol for rapid communication and (where possible) coordination regarding X-ray counterpart searches and follow-up among *Swift*, *NuSTAR*, *NICER, Chandra, XMM, IXPE*, and *XRISM* (Slide 28) would be beneficial and may reduce redundancy.
- Additional funding to increase staffing at the Operations Center would enable a reduction in the response time to GW-EM ToO requests (currently 48 hours on a best-effort basis). For the rare bright events (i.e., on-axis, nearby), or those too near the Sun for other X-ray facilities to observe, such a capability may be critical to characterize the X-ray counterpart.
- See also Slides 29, 30, and 34 for Mission-independent findings.

NICER - Mission Specific Findings

- A protocol for rapid communication and (where possible) coordination regarding X-ray counterpart searches and follow-up among *Swift*, *NuSTAR*, *NICER, Chandra, XMM, IXPE*, and *XRISM* (Slide 28) would be beneficial and may reduce redundancy.
- Additional funding recommended by the 2019 Senior Review panel to increase staffing at the Operations Center will enable a reduction in the response time to GW-EM ToO requests, particularly outside normal business hours. For the rare bright events (i.e., on-axis, nearby), such a capability may be critical to characterize the timing properties of the X-ray counterpart.
- See also Slides 29, 30, and 34 for Mission-independent findings

XMM (US-GI only) - Mission Specific Findings

- A protocol for rapid communication and (where possible) coordination regarding X-ray counterpart searches and follow-up among *Swift*, *NuSTAR*, *NICER, Chandra, XMM, IXPE*, and *XRISM* (Slide 28) would be beneficial and may reduce redundancy.
- Where possible, prioritizing the processing and dissemination of GW-EM observations would enable more efficient and effective follow-up by the community (Slide 29).
- See also Slides 29, 30, and 34 for Mission-independent findings

JWST - Mission Specific Findings

- For GW-EM science, the community strongly favors shorter (≤ 1 month) proprietary periods, as this was believed to significantly benefit scientific discovery potential, as well as career development and recognition of the contributions of early career researchers.
- Additional joint observing programs for JWST, where scientifically relevant, would be fruitful. For GW-EM science, joint programs with HST and/or ground-based NIR facilities (e.g., Gemini) would enable comprehensive characterization of kilonova evolution, and thus appear particularly relevant.
- See also Slides 29, 30, and 34 for Mission-independent findings

WFIRST - Mission Specific Findings

- For WFIRST, a robust ToO program with a response time requirement of < 48 hours and a ToO data latency requirement < 12 hours would enable kilonova discovery for the reddest events. Such a capability may be uniquely sensitive to counterparts from black hole - neutron star mergers (Slide 27).
- See also Slides 29, 30, and 34 for Mission-independent findings.

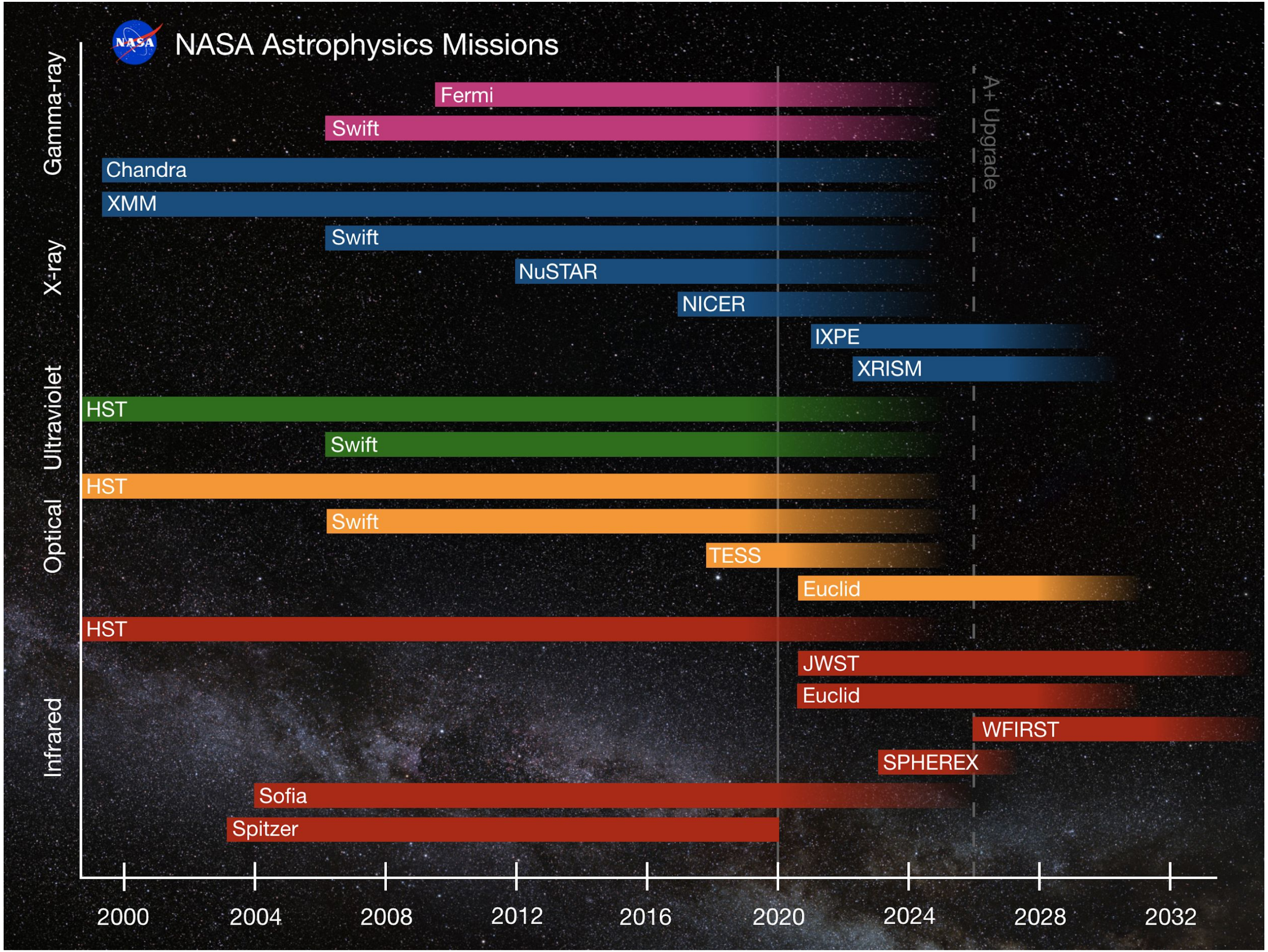
IXPE - Mission Specific Findings

- A protocol for rapid communication and (where possible) coordination regarding X-ray counterpart searches and follow-up among *Swift*, *NuSTAR*, *NICER, Chandra, XMM, IXPE*, and *XRISM* (Slide 28) would be beneficial and may reduce redundancy.
- See also Slides 29, 30, and 34 for Mission-independent findings.

TESS - Mission Specific Findings

- A reduced latency of the processing and availability of full-frame images (currently 1 month), even if unaccompanied by detailed quality metrics, would allow TESS observations to play a more timely and thus important role in GW-EM follow-up.
- See also Slides 29, 30, and 34 for Mission-independent findings.

Backup


NASA
NASA Astrophysics Missions
Gamma-ray
X-ray
Ultraviolet
Optical
Infrared
Fermi
Swift
Chandra
XMM
Swift
NuSTAR
NICER
IXPE
XRISM
HST
Swift
HST
Swift
TESS
Euclid
HST
JWST
Euclid
WFIRST
SPHEREX
Sofia
Spitzer
A+ Upgrade
2000
2004
2008
2012
2016
2020
2024
2028
2032

arXi

Table 2: Present (P) and future (F) electromagnetic facilities that are able to observe faint/distant counterparts to GWs. Detection Limit (**DL**, 1 hr exposure time) for UV, optical, and near-IR facilities are expressed in AB magnitudes, for X-rays in $10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{2}}$, and for radio in μJy. Distance reach (**D** in Mpc) of facilities for GW170817-like events are shown.

	Facility	**DL**	**D**
Gamma-rays	*Fermi* P	S/N 5	80
	AMEGO F	S/N 5	130
X-rays	*Swift* P	S/N 5	~80
	Chandra P	30	150
	ATHENA F	3	480
	Lynx F	6	450
	STROBE-X F	S/N 5	120
UV	HST (im) P	26	2000
	HST (spec) P	23	400
Optical Imaging	Subaru P	27	3200
	LSST F	27	3200
Optical Spec.	Keck/VLT P	23	500
	Gemini Obs. P	23	500
	GMT F	25	1265
	TMT F	25.5	1592
	E-ELT F	26	2005
Infrared Imaging	WFIRST F	27.5	4800
	Euclid F	25.2	1700
Infrared Spec.	Keck/VLT	21.5	481
	GMT F	23.5	762
	TMT F	24	960
	E-ELT F	24.5	1208
Radio	VLA (S) P	5	91
	ATCA (CX) P	42	51
	ngVLA (S) F	1.5	353
	SKA-mid (L) F	0.72	634

Joint Observing and Proprietary Periods

<u>Joint Observing:</u>

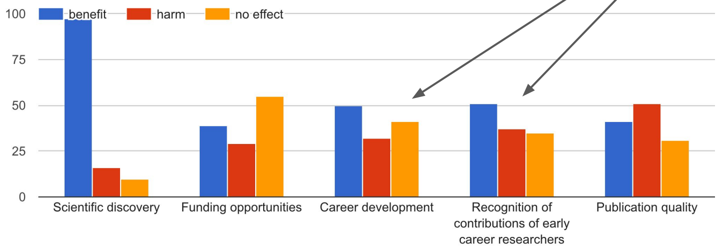
- Only 27% (30%) apply for JO Programs between NASA (NASA-GB) missions.
- Existing JO programs generally sufficient (70% ‘yes’)
- Specific needs?
  - More NSF+NASA opportunities (ALMA-NA
  - NASA+ESO opportunities (e.g., VLT with N
- Single proposal call? People were intrigued bu

Supports Rec #8b, c

<u>Proprietary Periods:</u>

- 81% of respondents in favor of <1 month PP (57% favor zero)
  - **Only 3%** favor 1 year (default for some missions?)

Surprising? 40% think it will benefit early career/career development.



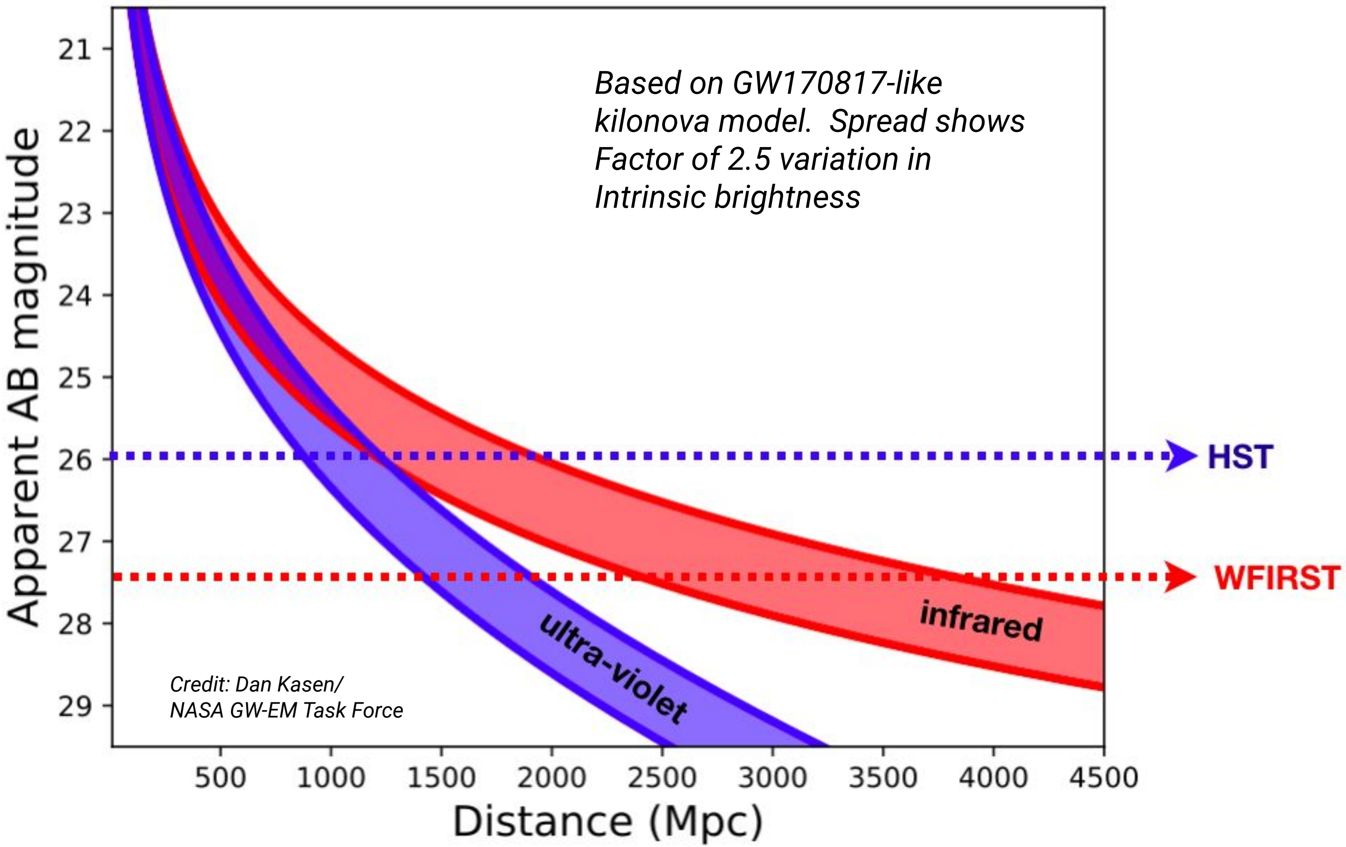
- 79% of respondents 0 PP will benefit science

Comparing to Rec #14, survey results in favor of <12 month (and majority <1 month) PP’s. Reasonable for missions with PP’s to let PI’s choose and ~12 month PP’s should not be the default for this science.

NASA-NSF Coordination

- GW-EM science would benefit from joint funding opportunities for coordinated science between ground- and space-based facilities
- Single well-supported standards for alerts and follow-up
- Open data policies (including NSF facilities, GW)

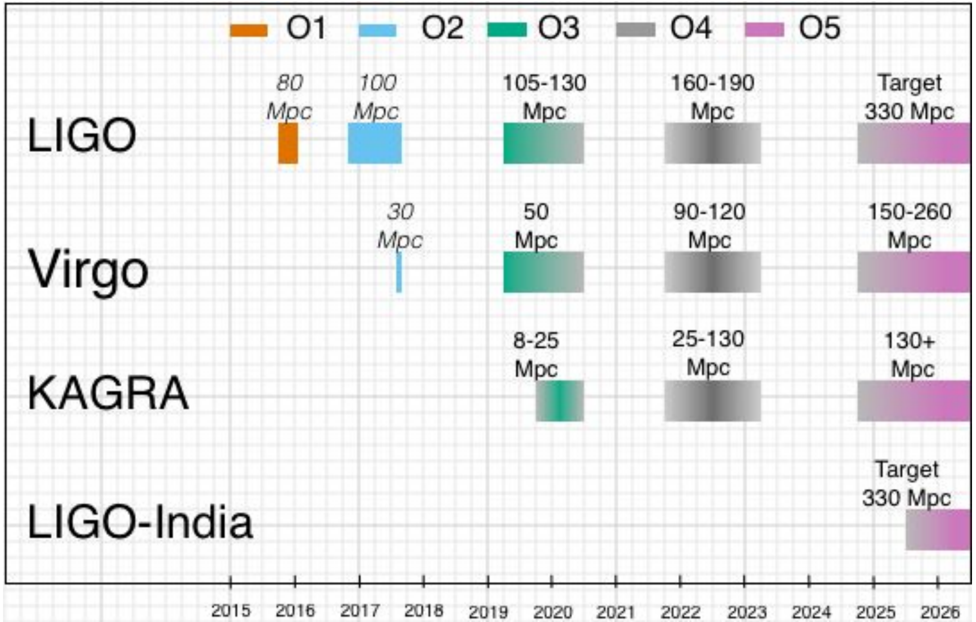
GW Counterparts: Kilonovae



Limits from one hour exposure time

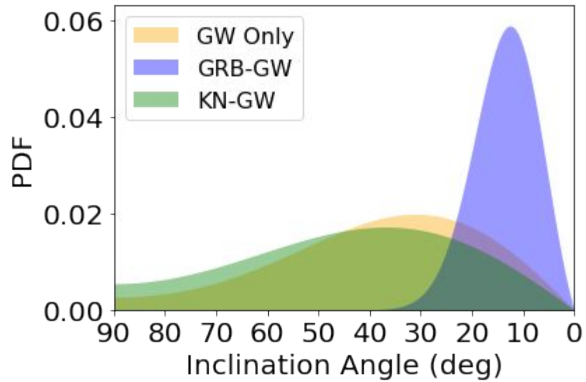
GW Neutron Star Merger Prospects

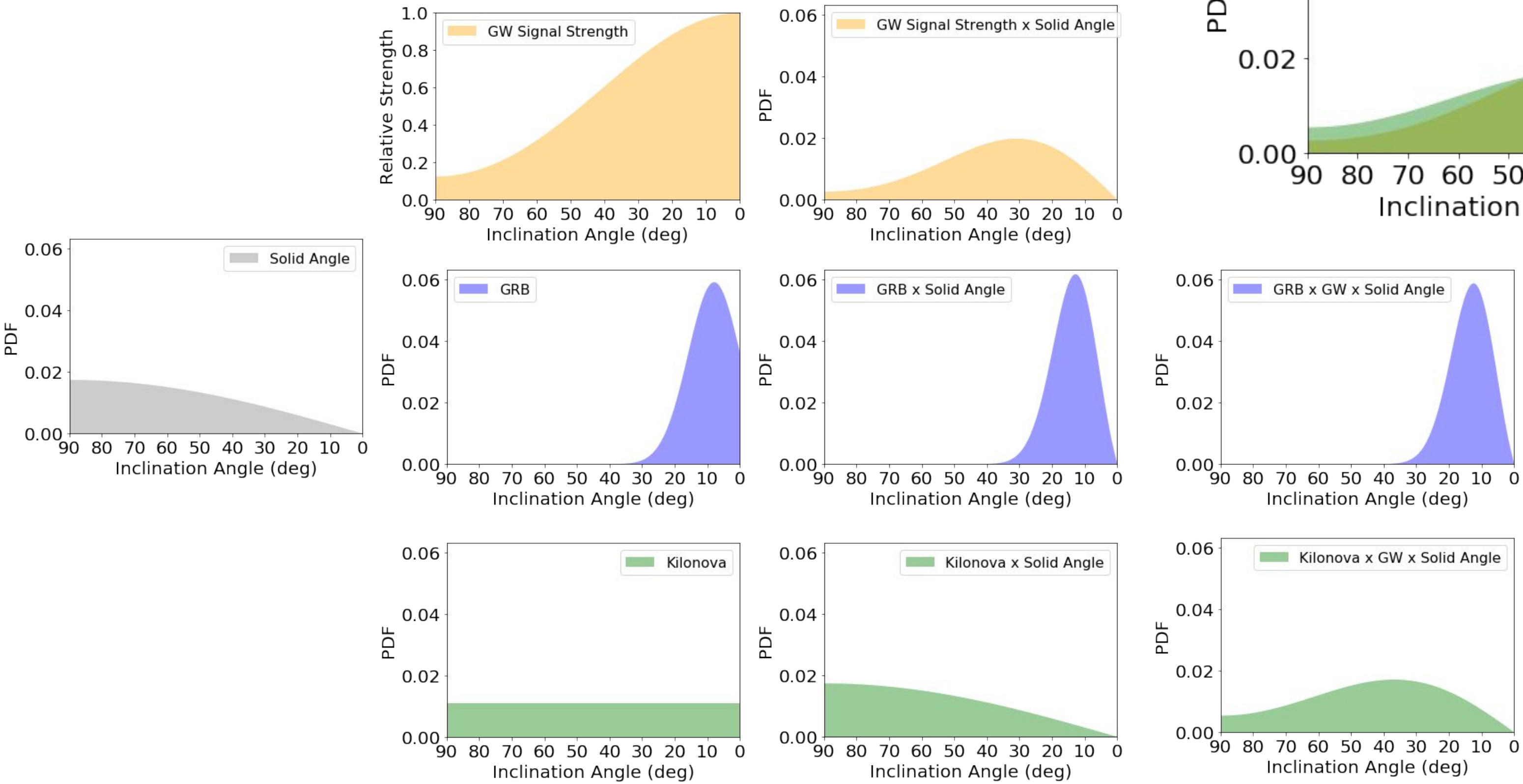
- Range = Sky and orientation averaged BNS distances
  - Merger rates ~ range^3
- GW Localizations improve with more detectors in network and SNR
- More distant events will have fewer detectors and weaker signals (given asymmetry in network)
- EM Counterparts will be harder to find with more distant mergers



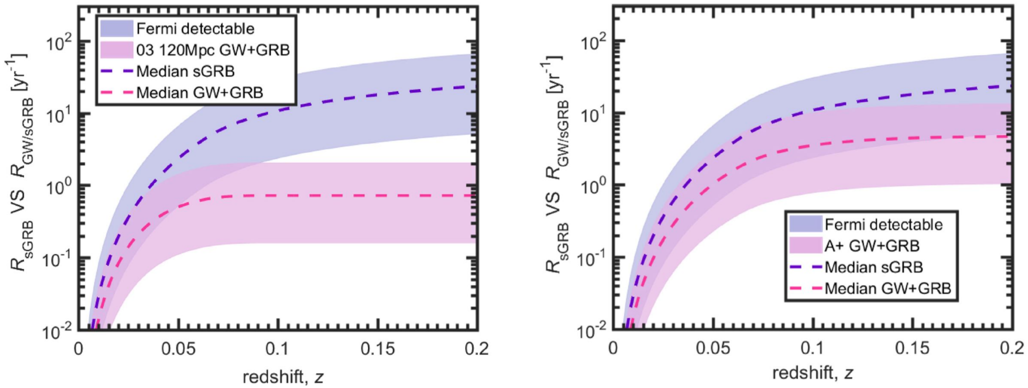
https://www.ligo.org/scientists/GWEMalerts.php

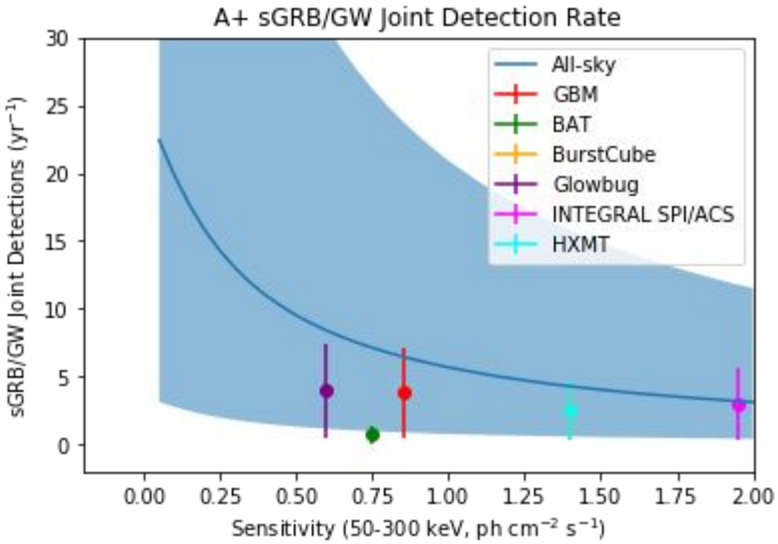
Viewing Angle Dependence



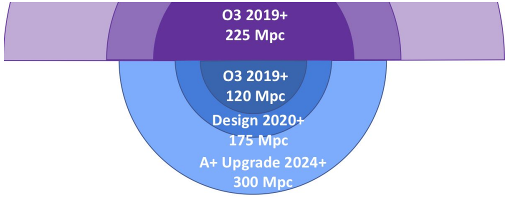


Short GRBs





O2 †	O3	aLIGO	A+ ‡	Voyager ‡
(2016-17)	(2019-20)	2021-	2024-	2030-
$0.14^{+0.30}_{-0.11}$	$0.58^{+1.21}_{-0.46}$	$1.23^{+2.55}_{-0.97}$	$3.10^{+6.45}_{-2.46}$	$7.53^{+15.66}_{-5.97}$
-	11%	7%	2%	0.4%



GW Range

Potential Changes for NASA facilities that would increase scientific return in GW-EM science

Changes for HST and Chandra:

- About a quarter of respondents said no changes needed (HST 23%, Chandra 33%)
- Roughly a quarter requested changes to each of
  - More ToO's (~28% for both H&C),
  - More time (~18% for both H&C),
  - Reduced latency (H-23%, C-13%)
- A small percentage (H-5%, C-9%) requested faster data availability, reduced proprietary periods.

Changes for Fermi, Swift, NuSTAR, TESS, NICER, XMM

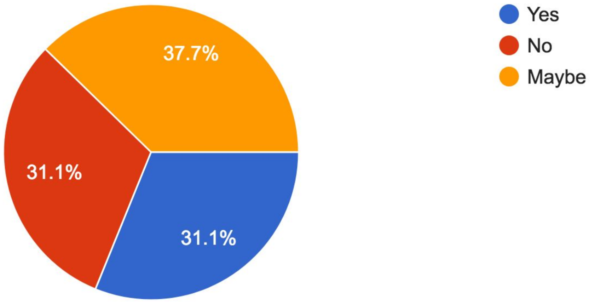
- A majority of respondents (~60%) requested no changes
- For most missions, 5-8% requested each of more ToO's, more time, reduced latency, faster data
- NuSTAR and XMM had somewhat higher requests for more time/ToO's (~15%)

Changes for future Missions:

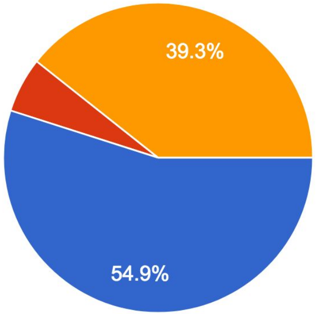
- About 18% had no requested changes for WFIRST/JWST, but 40% for XRISM, IXPE
- For all missions, roughly 30% requested more time for GW/EM for all missions and more multi-wavelength coordination
- For WFIRST/JWST about a quarter requested faster response time; only ~10% did for XRISM/IXPE

Diversity

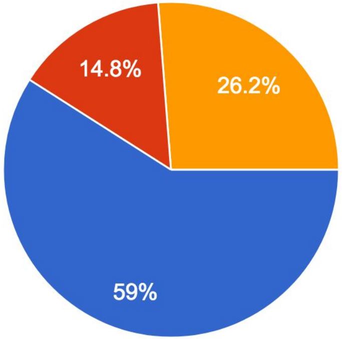
- 1) Do you think that early career researchers are getting sufficient r
to the emerging field of GW-EM science?
    - Respondents largely split
    - Results: 31% Yes, 31% No, 37% Maybe



- 2) Would the option of multiple co-PI's on GI/GO/ROSES proposals benefit ea
researchers in GW-EM science?
    - Majority of respondents believe multiple Co-Is would help
    - Results: 55% Yes, 38% No, 5.7% Maybe

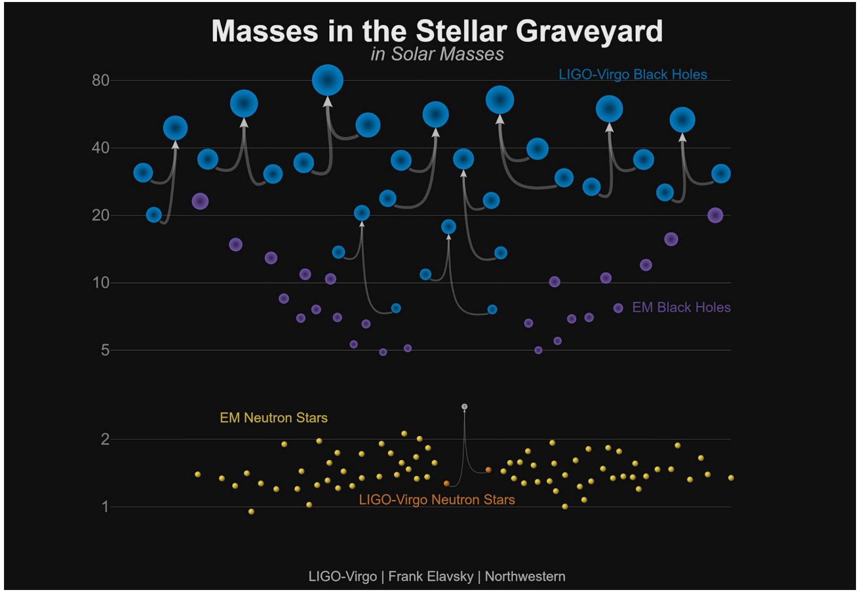


- 3) Are you in favor of double-blind proposal reviews for all NASA G
programs?
    - Majority of respondents are in favor of double-blind reviews
    - Results: 59% Yes, 26% Maybe, 15% No



Brief History of Observational Gravitational Wave Astronomy

- Advanced LIGO (2015) and Advanced Virgo (2017) began regular detections of stellar mass binary black hole mergers
  - No firm counterparts to date
  - Follow-up observations with NASA facilities
- First binary neutron star merger GW170817 coincident with GRB 170817, led to enormous follow-up campaign, detection of kilonova, afterglow, host galaxy
- No other firm counterparts detected to date



Ic. **Increased coordination between missions and follow-up community**

Mission-specific findings:

- Hubble: more transparent coordination for early follow-up of GW triggers especially when multiple GO programs are triggering ToOs would be helpful
- Swift
  - Note - UVOT pre-imaging survey of nearby galaxies is an excellent resource for GW-EM follow-up observations.
  - Note - BAT-GW subthreshold search
  - UVOT online light curve tools - more advanced automated tools
- Fermi
  - Public release of the software used to automatically generate GRB localizations (RoboBA), so that its performance can be independently compared to analogous external algorithms and/or augmented by community members. - targeted search too would be beneficial
  - Predictive pointing information tool for both GBM & LAT
  - Prompt automated joint GBM+GW localizations, with updates as new maps come out
  - Note - GBM-GW subthreshold search
  - LAT GW follow-up table
  - GBM GW follow-up table
- NICER
  - Completing the public visibility-calculation software would be useful

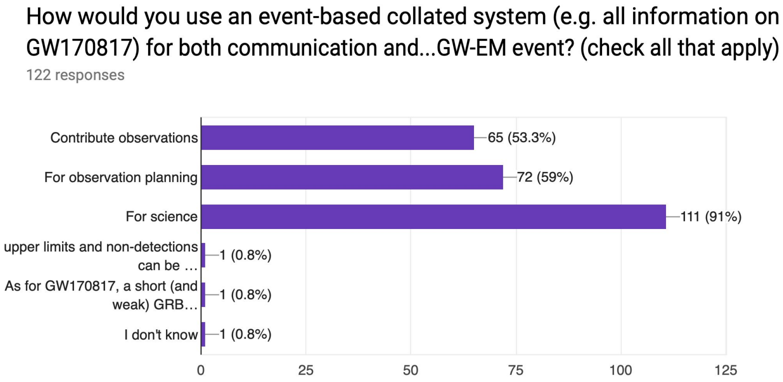
Archival Resources

- 1) How do you use mission archival data for GW-EM science?
  - Vast majority of users use pre-explosion imaging and historically analogous sources
- 2) Do mission archives spread across multiple system (e.g. HEASARC, MAST) hinder your GW-EM science?
  - Respondents split as to whether this is a serious issue
  - Results: 37.8% Yes, 37.8% No, 24.5% Maybe
- 3) Are NASA archives reasonably structured to facilitate GW-EM research? What could be better?
  - Many respondents feel that the interfaces are outdated
  - Would like better search web interfaces and API like access
  - Generally users are not fans of the HEASARC browse tables
  - Central archive of archival imaging
  - Central repository of publically accessible imaging associated with GW searches

Transient Communications Systems

- Existing Systems
  - GCN: Circulars - 89%, Notices - 61%, 3rd party methods of receiving notices - 30%
  - ATel: 53%
  - Transient Name Server - 35%
  - GW App - 20%
  - AMON: 11%
- Improvements Desired (ranked - top 3)
  - Better searchability
  - Easier machine readability
  - Modern protocols for submission/notification
- Event based collated system would be used for
  - Science
  - Observation planning
  - Contributing to system

- Other Feedback
  - GCN Circular delays - already being addressed
  - Tool for coordinating and visualizing observations of large localizations
  - Collated candidate counterpart identifications
  - Collate GCN reports on each event
  - Better integration of GW/NASA archives
  - Coordinated sub-threshold searches
  - A centralized real-time, multi-wavelength public logging system



GW Network Performance: O3+O4 (2019-2023)

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}

		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	250 – 310	310 – 390	250 – 340
O4	HLVK	29 – 48	48 – 69	33 – 47

LIGO, Virgo, and Kagra Collaborations et al. arXiv:1304.0670 (updated 9/2019)

GW Network Performance: O5 (2025+)

		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	-	30	50	90 – 120	150 – 260
	KAGRA	-	-	8 – 25	25 – 130	130+

Upgrades made for the O5 observing run (~ 2025), as part of the NSF-approved “A+” configuration, correspond to an increase in event rate of ~ **20x**. Binary black hole mergers will be detected on a ~daily basis, while binary neutron star mergers will be discovered at a rate of ~ 1 per week. While there are considerable uncertainties in these rates, this nonetheless represents a “state change” in gravitational wave astronomy.